Investigation of RF Emissions From Wireless Networks as a Threat to Avionic Systems

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October 2002

Abstract

The paper focuses on understanding and obtaining preliminary measurements of radiated field (RF) emissions of laptop/wireless local area network (WLAN) systems. This work is part of a larger research project to measure radiated emissions of wireless devices to provide a better understanding for potential interference with crucial aircraft avionics systems. A reverberation chamber data collection process is included, as well as recommendations for additional tests. Analysis of measurements from devices under test (DUTs) proved inconclusive for addressing potential interference issues. Continued effort is expected to result in a complete easily reproducible test protocol. The data and protocol presented here are considered preliminary.

Introduction

The use of wireless technology onboard commercial aircraft will continue to be of concern to the aviation industry. Airlines are interested in use of wireless technology to provide in flight Internet service, as well as, possible security and monitoring functions. Also, while the airlines would prefer to impose fewer restrictions on passenger use of Personal Electronic Devices (PEDs), new PEDs will include more advanced technology including wireless communications. Currently the FAA prohibits the use of intentional transmitters, such as cellular phones (wireless technology), while the airplane is taxiing down the runway, ascending, descending, and landing because of their potential to interfere with the navigational equipment. The most likely type of interference results from spurious emissions from PEDs that couple into the antenna ports of the communication and navigational equipment. Navigation systems such as Distance Measuring Equipment (DME), Global Positioning System (GPS), Instrument Landing System (ILS), Traffic Alert and Collision Avoidance System (TCAS), and Very High Frequency Omnidirectional Range (VOR), utilize the frequency bands that the final test protocol will thoroughly investigate.

Since PED technologies are advancing rapidly, they allow users to have more functionality in one hand held device. Some devices are incorporating multiple technologies together in one device such as wireless LANs, cellular phones, personal digital assistants (PDAs), web browsers, MP3 players and laptop computers. Hence, detecting if a carried on device is an intentional transmitter will be difficult. With respect to wireless LANs, travelers want the capability to use their PED to connect with other PEDs or the Internet as they do in their home and office. Therefore, NASA Langley Research Center is conducting research to investigate the use of portable devices on board airplanes.

The High Intensity Radiated Fields Laboratory will devise a final test methodology to assess the new wireless technology threat to aircraft systems. Preliminary wireless network systems tests were conducted in a reverberation chamber, since the test method is simpler, more thorough, and has better repeatability than the standard anechoic method. Unlike the anechoic method, which yields results in field strength at a given distance from the test device, the reverberation method measures the total radiated power from the device. However, future tests will incorporate peak radiated amplitude measurements from a semi-anechoic chamber based on a modified DO-160 procedure similar to that in DO-233.

Preliminary investigation of wireless network (802.11b and Bluetooth) emissions produced insight as to which frequency band contained spurious radiated emissions. Testing began with a chamber and cable calibration. Losses measured during calibration were subtracted from the peak-radiated amplitude yielding the true total radiated emissions emitted by the DUT. A baseline reference was done to separate wireless data link emissions from those of portable computers. The data plots, in the analysis section of the paper, prove that the wireless technologies meet FCC 15.209 and Bluetooth 1.1 standards. However, wireless units will need to meet the RTCA DO-160D standards for approval for use on board aircrafts.
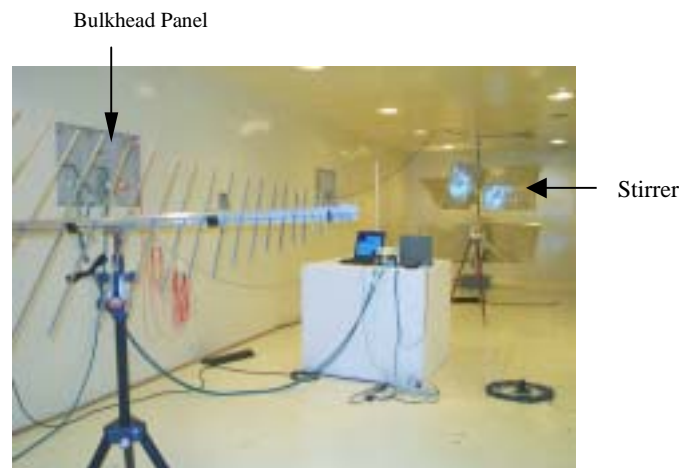
Reverberation Chambers

A reverberation chamber was used for this initial investigation of WLAN products. Properties of this type of chamber simplify the process of measuring emission data from the computers and wireless data links.

Properties of Reverberation Chambers

Even though reverberation chambers have been in existence for over fifty years, engineers today are finding even more ways to utilize them, and their use is becoming increasingly popular. Engineers have proven that using reverberation chambers to test electromagnetic interference is cheaper, faster, and more realistic than tests conducted in a semi-anechoic chamber where the DUT's orientation and location should be taken under consideration.   A reverberation or "mode-stirred" chamber is a large RF shielded metallic cavity used to test electromagnetic shielding effectiveness, susceptibility, and radiated emissions in a manner that is highly reproducible and technically thorough. By design, reverberation chambers provide statistically homogenous and isotropic electromagnetic field distributions. Large reflective mechanical stirrers rotate during testing to help mix standing waves inside the chamber.

The stirrer reflects the electromagnetic waves onto walls, ceiling, and floor thereby creating an electromagnetic field equal in magnitude to the vector sum of all the reflected waves at any point [1]. Reflected waves that arrive at a given point will have a different magnitude according to the number of reflections that previously occurred. The phase for each wave will be different from one another since the path lengths to reach a given point is different. Therefore, allowing the stirrer to change position causes the magnitude and phase of reflected waves to be different at every point in the chamber [2]. The stirrers effectively enable collecting statistical field emissions data inside the chamber with an antenna positioned in a single location.

Bulkhead Panel

Stirrer

Figure 1. Reverberation Chamber with DUT

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HIRF Laboratory Facility

All DUT tests were conducted in reverberation chamber A in the laboratory facility. Chamber A was chosen because it provides the lowest useable frequency of operation for the testing. A field uncertainty of +/- 6 dB can be obtained at 80 MHz in this chamber [3]. To achieve a more suitable performance, the lowest frequency chosen was 100 MHz, which established a number of modes over the minimum required sixty modes for an effective chamber. At this frequency, the chamber field uniformity is approximately ±2 dB, according to the standard deviation of 30 measurements of maximum electric field, and continues to improve at higher frequencies.
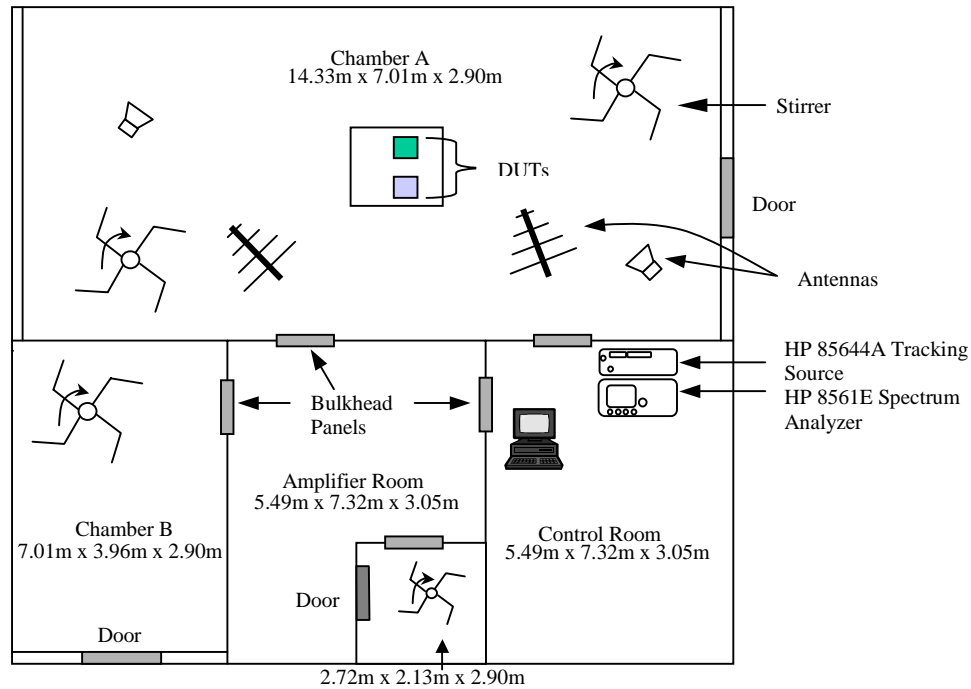
Figure 2. HIRF Lab layout

The dimension of the chamber determines the lowest frequency that will achieve a sufficient mode density to operate effectively. Since this chamber's electromagnetic environment has been characterized and documented by the National Institute of Standards and Technology, there is no need to use the equation to calculate the lowest frequency limit for this chamber. Since the two equations to calculate the lower frequency limit and total number of resonant modes within the chamber at a given frequency are outside the scope of this paper, refer to [4,5] for a detailed explanation.

Basic Test Configuration

Antennas

The emissions tests were run over a wide frequency band of 100 MHz to 5 GHz. Two different types of antennas were utilized to cover the frequency range and to collect the most accurate data. A log periodic antenna with a range of 100 MHz to 1.1 GHz was used to take measurements in the two lower frequency bandwidths, 100 MHz – 300 MHz and 300 MHz – 1 GHz. In the higher frequency band of 1 GHz – 5 GHz, a double ridge guide horn antenna was employed. The ridges inside the horn shaped

structure allow the antenna to collect emissions within a broad frequency band. Certified testing range for this antenna is from 1 GHz to 18 GHz.

Spectrum Analyzer and Agilent Visual Engineering Environment Software

Chamber configuration for emission measurements consists of a receive antenna positioned inside the chamber and connected to the spectrum analyzer (SA) with coaxial cable through the bulkhead panel. In the control room, the SA is connected to the computer, with monitoring software, by a General Purpose Interface Bus (GPIB) cable. Figure 5 illustrates this set-up.

Runtime EMI Environment Monitor software was created with Visual Engineering Environment (VEE) to aid the test engineer in accumulating the data into an Excel spreadsheet. This monitoring program controls SA settings. A test engineer enters values for each parameter in the Operation Menu. Data directory and filename, start and stop frequency, resolution bandwidth, sweep time, reference level, dwell time, and attenuation are the parameters that are set and displayed in the spectrum analyzer stats section of the interface screen. As a test begins the software commands the spectrum analyzer into a "max hold" setting. A single emissions measurement concludes when the specified period of wait time or dwell time is complete before downloading corresponding frequencies and maximum signal level amplitudes of the signal trace. The spreadsheet, as shown in Figure 6, contains the test parameters in the first two rows and the third row starts the data collected, containing frequency in the first column with corresponding radiated power in the second column.
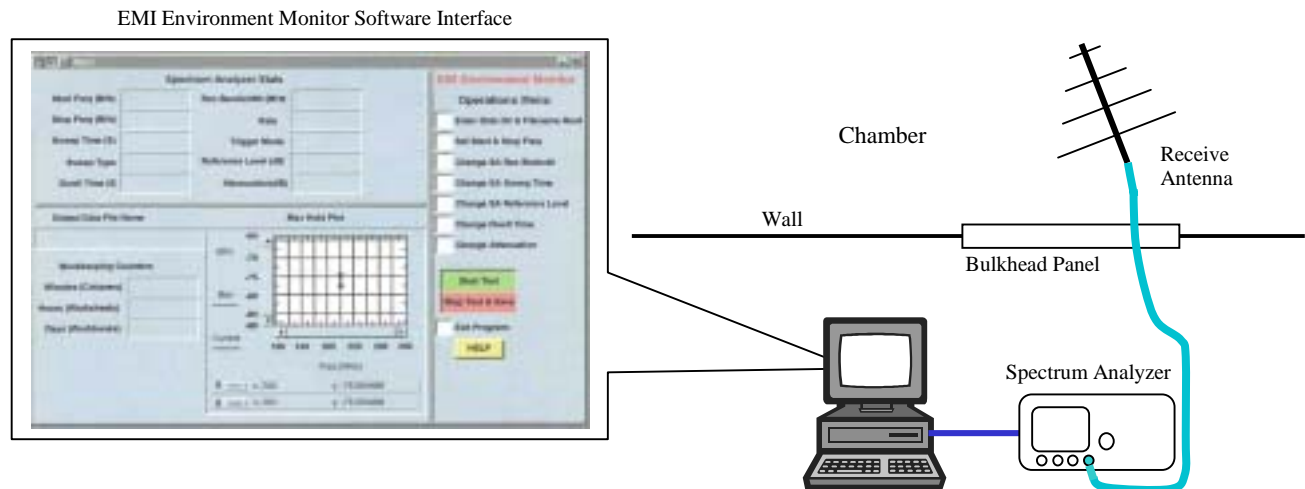
Figure 5. Hardware and Software Configuration for emission tests

Date	Time	Start Freq	Stop Freq	Res Bndwdth	Swp Time	Ref Lvl	Atten
16:07:01	15:21:02	100.00	300.00	0.10	2.00	-40.00	0.00
100.00	-70.50						
100.33	-71.00						
100.67	-70.17						
101.00	-71.00						
101.34	-72.17						
101.67	-71.50						
102.00	-71.83						
102.34	-69.50						

**Figure 6.** Excel Spread Sheet that contains the data

Testing Procedure

Chamber and Cable Calibration

Calibration of the test environment is the first step in gathering emissions data. This process provides an opportunity for verification of a properly working receiver antenna and efficient cables. All tests were conducted using the same parameters for the SA in three frequency bands.

Start and Stop Frequency	100 – 300 MHz
	300 – 1000 MHz
	1000 – 5000 MHz
Resolution Bandwidth	100 kHz
Sweep Time	2 sec
Reference Level	-40 dB
Dwell Time	120 sec
Attenuation	0 dB

Laptop computers (DUTs) are placed on a large Styrofoam block inside the chamber. This particular Styrofoam's dielectric constant is very similar to free space and is considered invisible by radiated fields. However, any other object placed inside the chamber may add loss and potentially affect the power level. 'Load' is the term for an object that absorbs some of the incident energy causing a loss to occur in the chamber power density. It is for this reason a chamber calibration is performed, so the chamber's cumulative loadings are characterized and later normalized out.
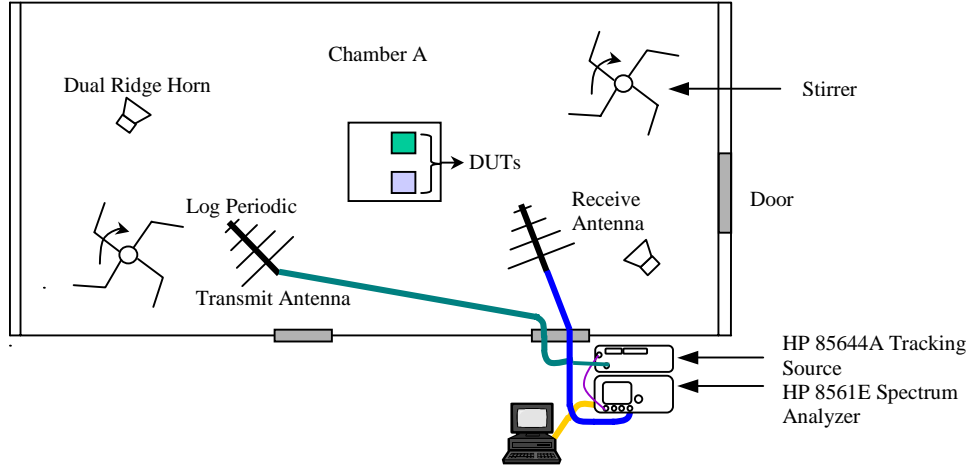
Figure 7. Chamber setup for radiated emission calibration measurement

Ely [unpublished data by J. Ely, Langley Research Center] describes the chamber loss value as being the relationship of the power transmitted into the chamber and power coupled out through the receive antenna. The power lost is primarily caused by the absorptions from transmit and receive cables, chamber walls and stirrers, and by other objects in the chamber. Figure 7 illustrates how the instruments are set up to measure all loss factors together and equation (1) is the mathematical expression.

$$\alpha_{CbrCal}(dB) = P_{Xmt}(dBm) - P_{Meas}(dBm) = \alpha_{Cbr}(dB) + \alpha_{RcvCbl}(dB) + \alpha_{XmtCbl}(dB) \tag{1}$$

where

$P_{Xmt}(dBm)$ = Transmitted Power from the tracking source (1mW).

$\alpha_{XmtCbl}(dB)$ = Transmitted cable loss from tracking source to transmit antenna connection.

$\alpha_{RcvCbl}(dB)$ = Receive cable loss from the receive antenna to the SA connection.

$\alpha_{Cbr}(dB)$ = Chamber loss

$\alpha_{CbrCal}(dB)$ = Chamber Calibration containing all the loss factors

It is essential to isolate the transmit cable loss in order to subtract the value out of the final data normalization equation. To directly measure the transmit cable loss, the cable must be disconnected from the transmit antenna and reconnected directly to the SA. Figure 8 shows the new set up for the measurement.
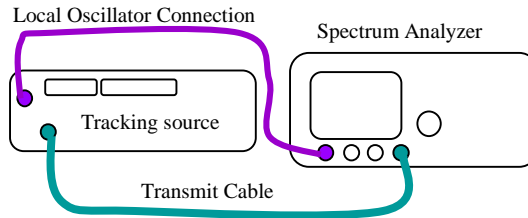
Figure 8. Transmit cable calibration

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$$\alpha_{XmtCbl}(dB) = \left| P_{Xmt}(dBm) - P_{Meas}(dBm) \right|_{TransmitCableCal} \qquad (2)$$

The chamber and transmit cable calibration values obtained for each frequency band are used in additional calculations to determine the total radiated power, discussed in the data normalization section, emitted from the DUT.

Laptop Computer Specifications

Four different brands of laptop computers were tested to quantify each of their emissions. Emission intensity is based on the radio frequency and electromagnetic field pattern generated by the entire system or device while in a particular mode of operation. Laptops included in this research are representative of older and newer models used by travelers today and are depicted in the table below. The models vary by processor speed, RAM, hard drive, and placement of chips and traces on the circuit boards.

Laptop Components	L1	L2	L3	L4
Processor speed	266 MHz	366 MHz	1 GHz	266 MHz
RAM	64 Mbytes	229 Kbytes	255 Mbytes	64 Mbytes
PCMCIA slots	2	2	2	2
Floppy drive	3 ½	3 ½	3 ½	3 ½
Hard drive	16.8 Gbyte	4 Gbyte	18.6 Gbyte	1.99 & 1.81 Gbyte
CD ROM	Yes	Yes	Yes	Yes
Sound	Yes	Yes	Yes	Yes
Video	Yes	Yes	Yes	Yes

Baseline Tests

Baseline references for each of the laptops were completed prior to inserting WLAN products for tests. A baseline provides emissions solely emitted by the laptop while operating at the same level of processor, memory access, disk read/write, and video activity. This makes it possible to separate radiated emissions from the wireless data link and those from the laptops.

The baseline tests were run for the purpose of identifying the emissions from a processed task. Data collected from each processed task overlapped in a graph created an envelope of maximum peaks emitted from the laptop (see Appendix A). Task names were inserted into the filename along with each brand of laptop and the designated frequency band to specify the measurement taken. Implemented task names and a brief description of each follow. Screensaver task uses the 3D Flowerbox design that comes standard with the Microsoft Windows 2000 Operating System. Under the screensaver menu options, the flower box was selected to be a large smooth checkerboard cube pattern that spins and blooms at maximum complexity. Internal Tran task is simply a hard drive file transfer from one folder to another. HD Tran MD task is a file transfer from the hard drive to a PCMCIA slot mounted Microdrive. Audio task plays an audio CD. In the future, collecting emissions from the laptop playing a DVD is important, since travelers with this feature in their laptop may watch a movie on long flights. Emissions solely collected from the laptops reveal the quality of shielding each manufacturer incorporates into their units for EMI protection and controlling spurious emissions.

Wireless Local Area Network

The following is a brief description of some of the current and future technologies adding versatility to an existing network in the home and workplace. Basic knowledge of their capabilities and modes of operation assist in conducting a fair investigation of the wireless units.

IEEE 802.11b

Overview

The term "wireless local area network" (WLAN) describes the transmission of data between computing devices using radio frequency (RF), which provides freedom to roam about a fairly spacious area. An organization called Wireless Ethernet Compatibility Alliance (WECA) devised the Wireless Fidelity (Wi-Fi) certification program to measure 802.11b equipment interoperability. 802.11b WLAN products must comply with Wi-Fi's standard of association and roaming capabilities, throughput, and required features such as 64-bit encryption to gain their logo for interoperability [6]. Thus Wi-Fi is interchangeable with 802.11b. Consumers are free to mix 802.11b products stamped with the Wi-Fi logo and communicate while roaming in and out of public coverage areas.

WLAN contains all the features of an Ethernet system without the hassle of cables. 802.11b operates in the unlicensed 2.4 GHz Industrial, Scientific, and Medical (ISM) frequency band. The exact band 802.11b operates in is 2.4 to 2.4835 GHz under US FCC 15.247 and 15.249 regulations. FCC Part 15.247 states that a system (intentional radiator) will use frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS) with additional guidelines. FCC Part 15.209 contain specific limits adhered to by wireless components on the field strengths of emissions from intentional radiators.

802.11b is an extension of IEEE 802.11 standard. In order to increase the data transfer rate, 802.11b utilizes DSSS, a modulation technique to allow a device to communicate at a higher rate by distributing its energy over a contiguous frequency band [7]. 802.11b communicates with a throughput of 11Mbps over a 22 MHz passband. In the 83.5 MHz frequency band there are fourteen 22 MHz wide sub-channels that the access point can use, of which three channels are non-overlapping. In North America the current maximum transmitted power for this wireless device is 100 mW, however, the standard allows 1000 mW if power control is built into the AP and PC cards. For more information about 802.11b read [6, 7].

There are two network topologies. Peer-to-Peer is the basic mode to create a network of two or more computing devices that share and transfer files. Infrastructure mode uses the access point (AP) to connect a mobile computer to the wired network.

Peer -to-Peer

This mode of operation is also referred to as an ad-hoc network. Figure 8 illustrates the configuration of an independent basic service set (IBSS) of stations equipped with wireless network interface cards (NIC). Figure 9 illustrates the NIC and its placement into a laptop computer. The wireless stations must be configured with the same radio channel in order to communicate with each other in a given coverage area. The IBSS is an on the fly connection between stations when an infrastructure containing an Ethernet backbone is not required for services or in places that simply don't have one.
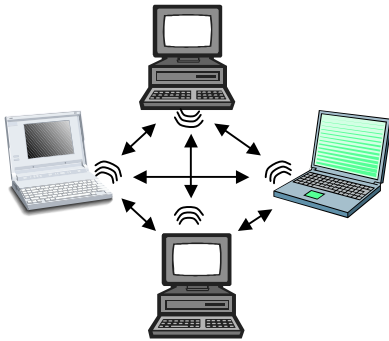
Figure 8. Peer-to-Peer (Adhoc) wireless connection
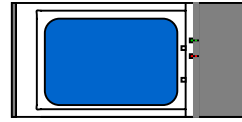
Figure 9. wireless NIC

Infrastructure

802.11b's more useful mode uses the AP to bridge any freely mobile station requesting connection to the network. The layout of two basic service sets (BSS) along with an extended service set (ESS) is shown in Figure 10. A BSS contains an AP connected to the wired backbone with wireless end stations. ESS is two or more overlapping BSSs connected to the same Ethernet backbone. In infrastructure mode the configuration of stations are required to have the same radio channel and extended service set identifier (ESSID). ESSID is a 32-character maximum case sensitive code known to an individual network and the wireless devices within that network. The stations can move in and out of cell coverage areas with ease. The AP and software will transmit information to enable a hand off to occur between the two APs.
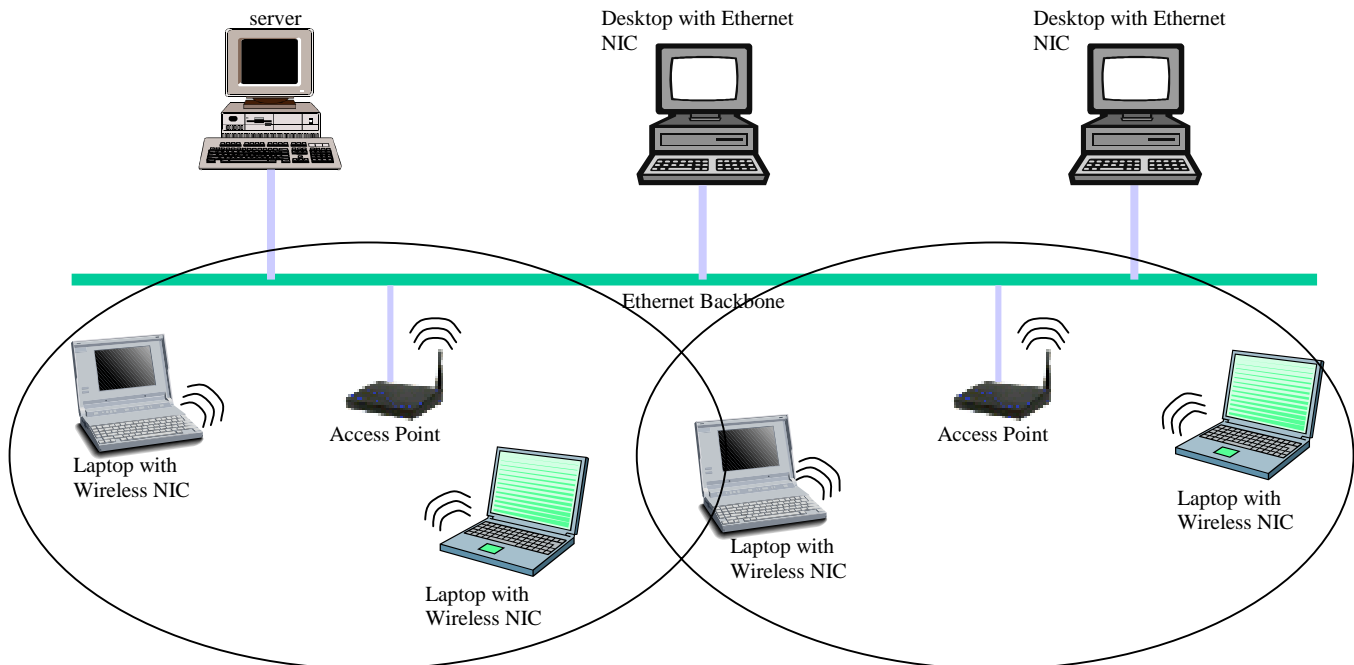
Figure 10. Infrastructure setup in BSS and ESS

Bluetooth

Leading communication and computer companies make up the Bluetooth Special Interest Group (SIG) that maintains specifications of the protocol profiles, testing and qualifications, interoperability and compatibility. Bluetooth is leading the wireless personal area network (WPAN) IEEE 802.15.1 standard. Bluetooth technology implements RF in order to replace proprietary cables that connect one device to another within a short range. An excellent example for implementing this technology is with a desktop computer and all the peripherals connected to it.

There are three power classes specified in the Bluetooth technology standards. Class 1 is 100mW (20dBm) with a radius coverage area of up to 100m. A Class 1 device is required to control its transmitter power by implementing a link with Link Manager Protocol (LMP) commands. The remote device wishing to communicate in a power controlled link measures its own receiver signal strength using a Receiver Signal Strength Indicator (RSSI). The measurement reported back determines if the transmitter on the other side of the link should increase or decrease its output power level. This enables all classes to communicate without damage to the RF front ends of the lower power classes. Class 2 is 2.5mW (4dBm) with a radius coverage area of up to 20m. Class 3 is 1mW (0dBm) with a radius coverage area of up to 10m. Environments that the Bluetooth enabled devices operate in determines the communication distance that can be achieved.

Like the 802.11b standard, Bluetooth operates in the ISM band of 2.4 to 2.4835 GHz producing a maximum data transfer rate of 1 Mbps. Bluetooth utilizes FHSS technique to reduce interference and fading [9]. This particular wireless technology frequency hops at 1600 hops per second with a 625μs dwell time for any of the 79 given channels, with a 1 MHz spacing.

Bluetooth eliminates wires by having units connect to each other using RF to form a piconet. A piconet consists of a unit acting as a master establishing links with up to seven clients. The Bluetooth link is achieved via identification of the master and synchronization of clocks between the master and the slaves. This information known only between the units within the piconet is called a hop channel. It is possible to expand a piconet to include more slave devices by placing an active slave into park mode and activating another [9,10].

The unique feature with Bluetooth, as compared to 802.11b, is the capability of voice transmission. Bluetooth supports three simultaneous operable voice channels. This enables the user to connect to the Internet with use of a Bluetooth equipped mobile phone.

Wireless Testing

802.llb configuration of the software is different for each manufacturer's product. The brand involved in these tests had a fairly straightforward software package. The 802.11b PC card could be configured in either ad-hoc or infrastructure mode. Once the two PC cards find one another through scanning an identical BSS ID is assigned to both to establish a communication link.

Another aspect to the setup is the network software within Windows OS. To gain access into another laptop's files, one has to see the other laptop under their network neighborhood. In order for this to occur, configuration of all communicating laptops had to participate in the same workgroup.

802.11b tests were conducted in each of the respective modes as previously mentioned, with one additional test outside the definition of the infrastructure mode. All of the following conducted tests

transferred sizeable files between the two linked laptops. Test case one dealt with ad-hoc. Ad-hoc had a simple setup that consisted of two laptops outfitted with wireless NICs placed approximately 12" apart with the cards pointing at each other to remain linked. A preliminary test to the infrastructure mode consisted of a file transfer through the AP without being connected to the network. The AP was placed in the adjacent control room outside the test chamber to keep noise from coupling into the chamber through its power cord. Antennas from the AP were brought into the chamber through the bulkhead panel and were extended by cables so that they could be in the middle of the two NICs (Figure 11). This was to reduce the multipath effects in the chamber, which disrupted the communication between the two wireless enabled devices. The preliminary test was to verify that the connection was working before moving on. Test scenario two was in the infrastructure mode with the Ethernet plugged into the AP.
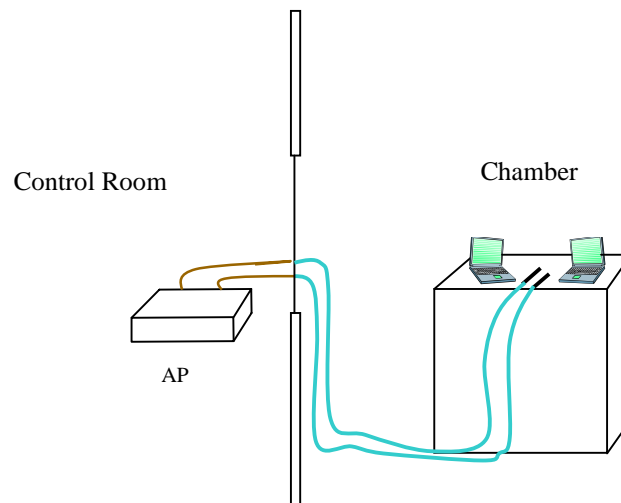
Figure 11. Laptops setup to communicate through the AP.

Bluetooth tests emulated the ad-hoc mode of 802.11b. Although there is a minor difference when transferring a file, the operator of the receive device has to approve it. Yet this might only be indicative to the sole WPAN our facility acquired to test.

A large file was created in order to obtain a transfer duration time of about 10 minutes. This was a sufficient amount of time to set the transfer up and get out of the chamber to take the measurement. Transfer time was also cushioned with the amount of time it takes for the automatic air piston chamber door to close. The dwell time for allowing the SA to receive all the maximum peaks for the frequency band was 2 minutes.

Preliminary investigation evaluated and assessed various cases for their relevance in the final test protocol. After the investigation concluded, we determined that two additional noise floor measurements should be acquired to compare the difference in emission levels during file transfer to that of just the two devices linked.

Problems Encountered

Network design can be a challenge when dealing with RF path loss. Path loss is loss of signal power between the two communicating devices. Factors that affect path loss are transmission distance, objects in the area, the room structure, and the transmission frequency. RF signals reflecting off of the objects in the surrounding environment while traveling to its destination cause multipath interference. Strong

multipath interference may lead to loss of transmission between the two communicating units.

With this in mind, the 802.11b had some difficulties with the RF signals inside the reverberation chamber. Intermittent problems with the NICs 'seeing' one another inside the chamber posed a challenge. This interference was likely caused by the NIC's antenna being overwhelmed with strong reflection of the original signal having similar magnitude, but being out of phase, this caused total cancellation resulting in signal loss. When the problem appeared, it was necessary to remove the two wireless laptops from the chamber to re-establish a link.

When the AP was introduced into the chamber and the wireless configuration software was switched to infrastructure mode, failure in communication between the devices occurred. In some cases, it was probably due to what occurred in the ad-hoc mode. Often times, the positioning and distance inside the chamber affected whether or not the computer could reach the AP. Yet, at times, position and distance could not be the culprit because the NICs were positioned close to the AP antennas. The position could be a result of the location of modes in the chamber. Multipath communication issues between two laptops placed in a metal enclosure, such as on board an airplane, will need to be addressed in further tests.

Data Normalization

As previously highlighted, all the data collected by the SA is normalized with the calibration data to reveal actual total radiated power (TRP) values. The formula is easily applied to the values in the data spreadsheets. While the calibrated signal source remains outside the chamber, it transmits a signal into the chamber and the received value is that of the total path loss. Chamber calibration measurement contains both transmit and receive cable path loss in addition to the actual chamber loss. Since the transmit cable path loss is no longer applicable during DUT emission measurements, it is subtracted out of the chamber calibration in the transfer function (H(f)) equation.

Equation (3) solves for total radiated power, $P_{TPR,}$ inside the reverberation chamber pertaining to emissions emitted by the DUT [unpublished data from J. Ely, Langley Research Center].

$$H(f)(dB) = \alpha_{CbrCal}(dB) - \alpha_{XmtCbl}(dB) \tag{3}$$

$$P_{TRP}(dBm) = P_{Meas}(dBm) - H(f)(dB) \tag{4}$$

where $P_{Meas}(dBm)$ = Power measured at SA

$\alpha_{XmitCbl}(dB)$ = Cable loss from the transmit antenna connector to power source

$\alpha_{CbrCal}(dB)$ = Chamber Calibration including all loss factors

Figures 12 and 13 demonstrate how the above expressions are applied. In Figure 11, column E (H(f)) is the summation of column D subtracted from column B.

A	B	C	D	E
Frequency (MHz)	α_{CbrCal} (dB)		α_{XmtCbl} (dB)	H(f) (dB)
300.00	-8.33		-1.33	-7.00
301.17	-8.50		-1.33	-7.17
302.34	-7.00		-1.33	-5.67
303.51	-8.00		-1.50	-6.50
304.67	-8.00		-1.50	-6.50
305.84	-7.50		-1.50	-6.00

Figure 12. Chamber calibration spreadsheet with transmit cable loss and calculated H(f).

The spreadsheet below is a portion of the emissions data from the DUT implementing the screensaver. Column E, true TRP from the DUT, is the summation of subtracting column D (H(f)) from column B, Measured data.

A	B	C	D	E
Frequency (MHz)	P_{Meas} (dBm)		H(f) (dB)	P_{TRP} (dBm)
300.00	-71.33		-7.00	-64.33
301.17	-72.00		-7.17	-64.83
302.34	-72.17		-5.67	-66.50
303.51	-70.67		-6.50	-64.17
304.67	-71.17		-6.50	-64.67
305.84	-71.50		-6.00	-65.50
307.01	-73.67		-4.83	-68.83

Figure 13. Sample file with the normalized amplitudes (total radiated power)

Analysis of Results

The Federal Communications Commission (FCC) limit line illustrated in the graphs is an estimated radiated emissions value. Estimated values were taken from Title 47, FCC 15.209 three meter emission limit. The limits given by the FCC are in microvolts/meter. In order to compare these figures to the laptop emission graphs, field strength measurements were converted to radiated power assuming an isotropic radiation pattern [1].
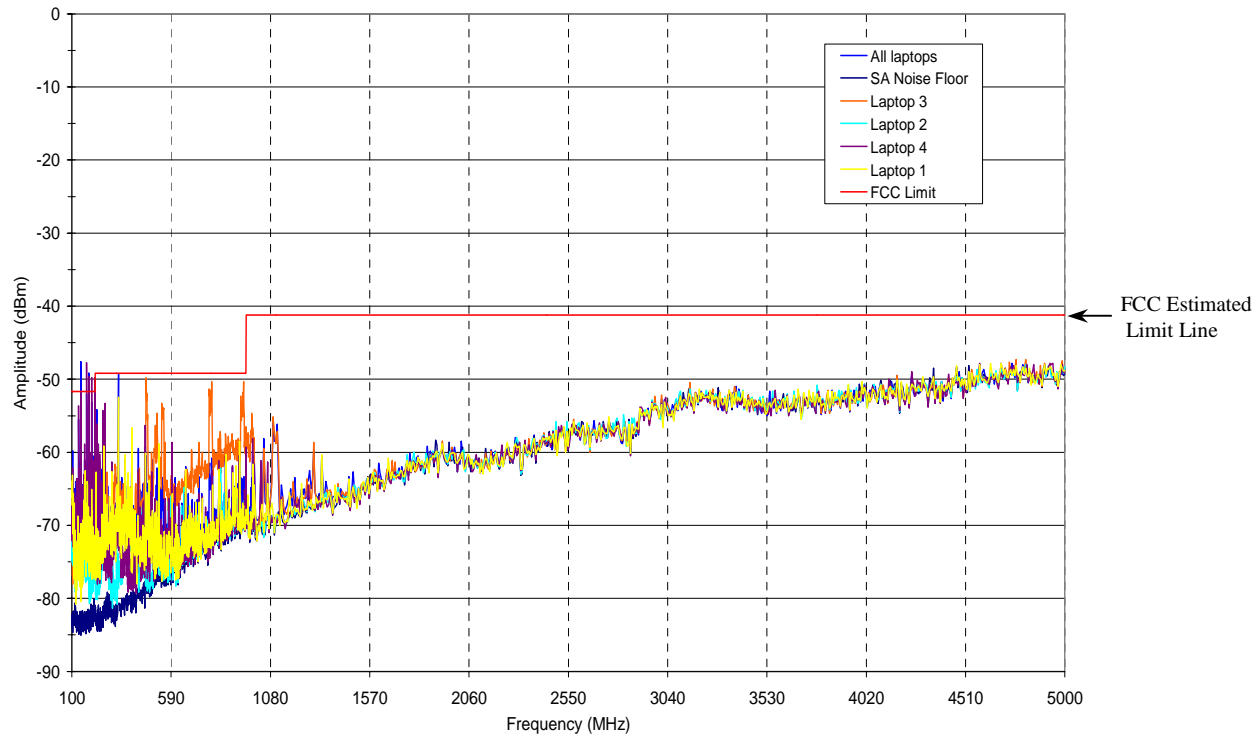
$$P_t = \frac{E^2 * 4\pi R^2}{120\pi} \tag{5}$$

$$= \frac{E^2}{30} \quad \text{watts, when R= 1 meter} \tag{6}$$

where P_t = Equivalent Radiated Power Watts

E = Measured Field Strength $^{Volts}/_{meter}$

R = Distance m

13

This furnished the total radiated power values for a 1 m limit (dBm) used to construct the estimation line.


Figure 14. Screensaver emissions graph.

Laptop, unintentional transmitter, emissions produced in the lower frequencies (100MHz to 1.1GHz) exceeded or remained just under the estimated limit line. Since aeronautical radio communication and navigation equipment operate in designated bandwidths within 100MHz to 1100MHz bands, there may be risk of interference from the peaks depicted in Figure 14. RF generated from the laptop may cause interference if coupling were to occur with select aeronautical frequency bands.

Another result from the baseline tests revealed that each computer has its own unique signature. A computer signature is a discernable pattern created by levels of maximum peak radiated power at various frequencies. This is possibly due to the variety of shielding techniques used by manufacturers to protect the computer's internal components. Moreover, within the given signature, different activities induced diversified RF emission levels. Appendix A contains graphs for the four laptops tested.

The graphs for the wireless LAN tests exposed a few relatively high emissions with respect to the FCC limit line from laptops performing file transfers while the access point was connected to the wired network. Again, the emissions are concentrated in the lower frequency band in both Figure 14 and Figure 15. Note that the spike is acceptable at approximately 2.46 GHz because the 802.11b Access Point is designated to operate at this frequency. The same is true for Bluetooth's several spikes in the range of 2.402 GHz – 2.482 GHz. In addition, the FCC estimated limit shown on the graph is a general restriction for non-intentional and intentional RF emissions, but does not pertain to the designated carrier frequency signal band for 802.11b and Bluetooth systems.

14
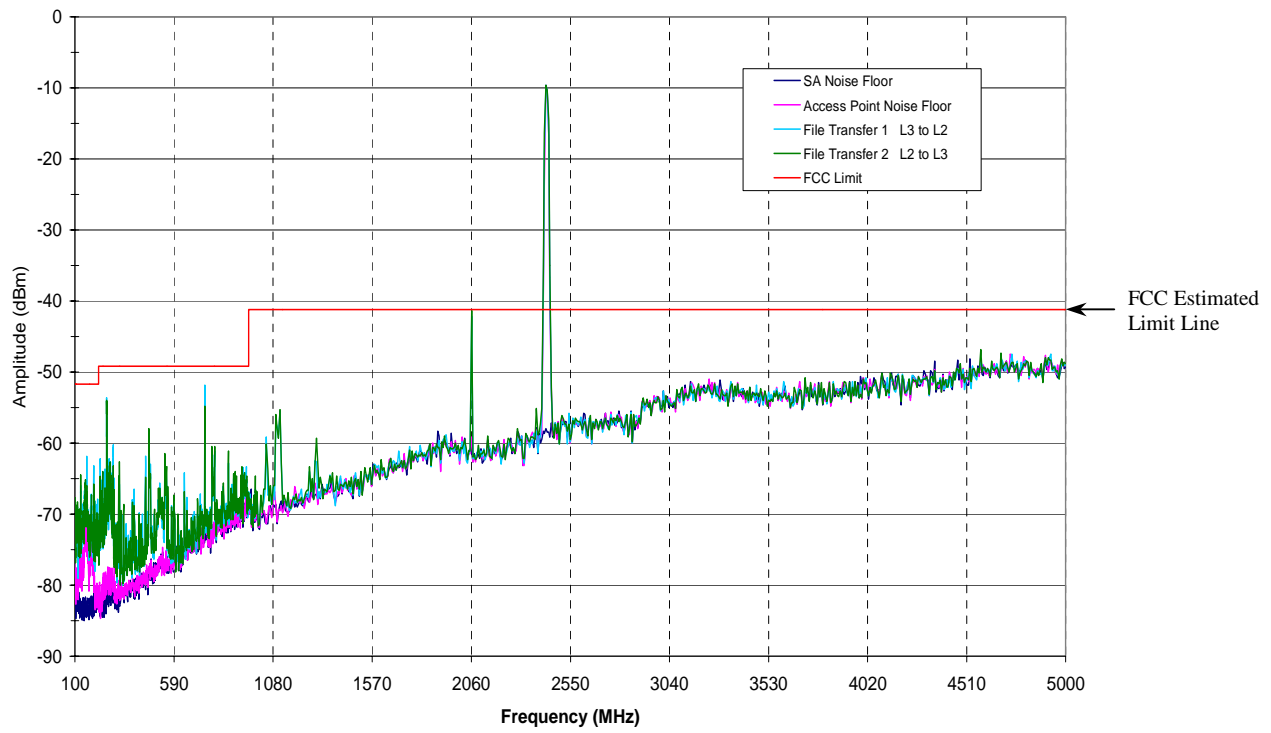
Figure 15. 802.11b graph for Infrastructure file transfer.
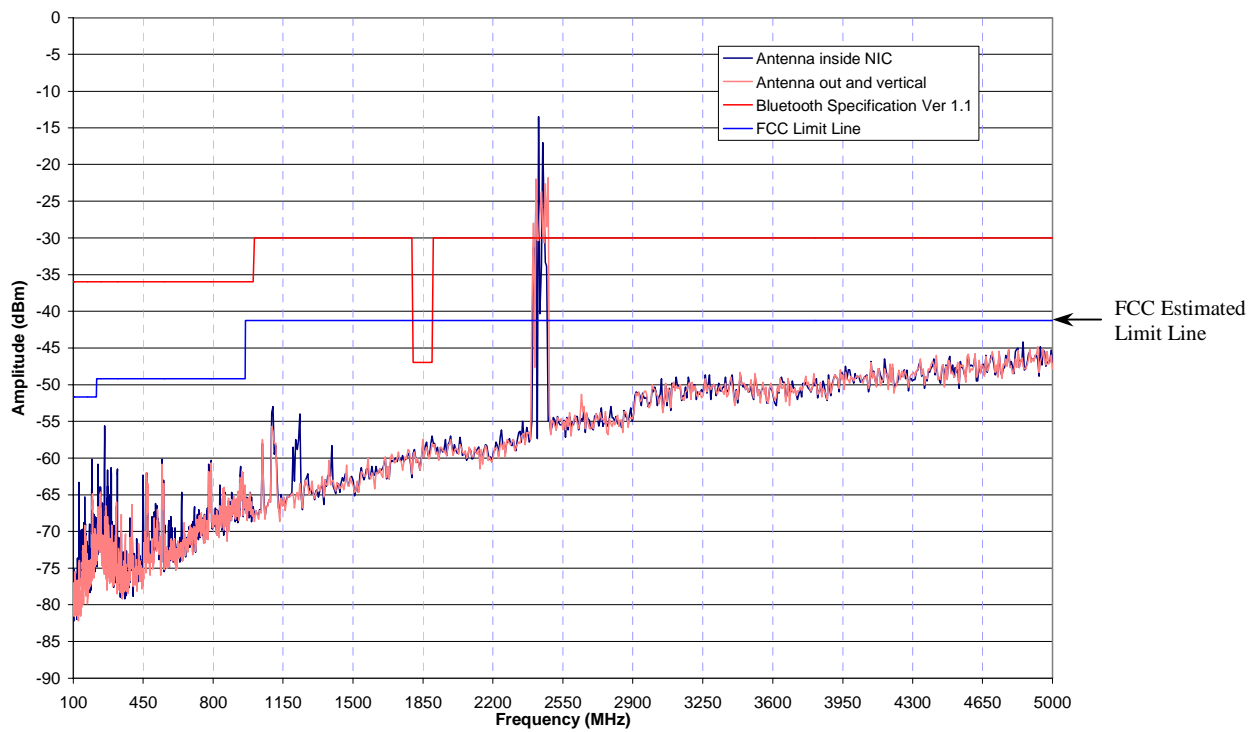
Figure 16. Bluetooth emissions while transferring files

15

If these technologies were to be permitted for use on board a commercial aircraft it is likely they would be required to pass RTCA DO-160D Category M, Airborne Equipment Qualification Limits for out of band emissions. The standard states equipment and wiring located in a passenger cabin and cockpit, not directly in view of aircraft radio receiver antennas are permitted when the emissions do not exceed the limits. VOR, Localizer, VHF Comm., Glideslope, TCAS, ATCRBS, GPS, and SatCom are in lower frequency bands where spurious emissions from the laptops/WLAN tend to be concentrated.

Conclusions

This preliminary study of emissions from laptop computers and wireless LAN technology provides a foundation for further testing. Tests spanned a broad frequency range for a general overview of spurious emissions from the DUTs. Analysis of this data was for electromagnetic interference (EMI) assessments for aircraft systems and other equipment as well.

It is evident that computers are the main source of significant radiated emissions. The screensaver emissions' graph illustrated this conclusion. 802.11b and Bluetooth devices tested emit a relatively small level of emissions that are added to those emitted by the computers, since WLANs assist computers in creating or maintaining a network and do not function on their own.
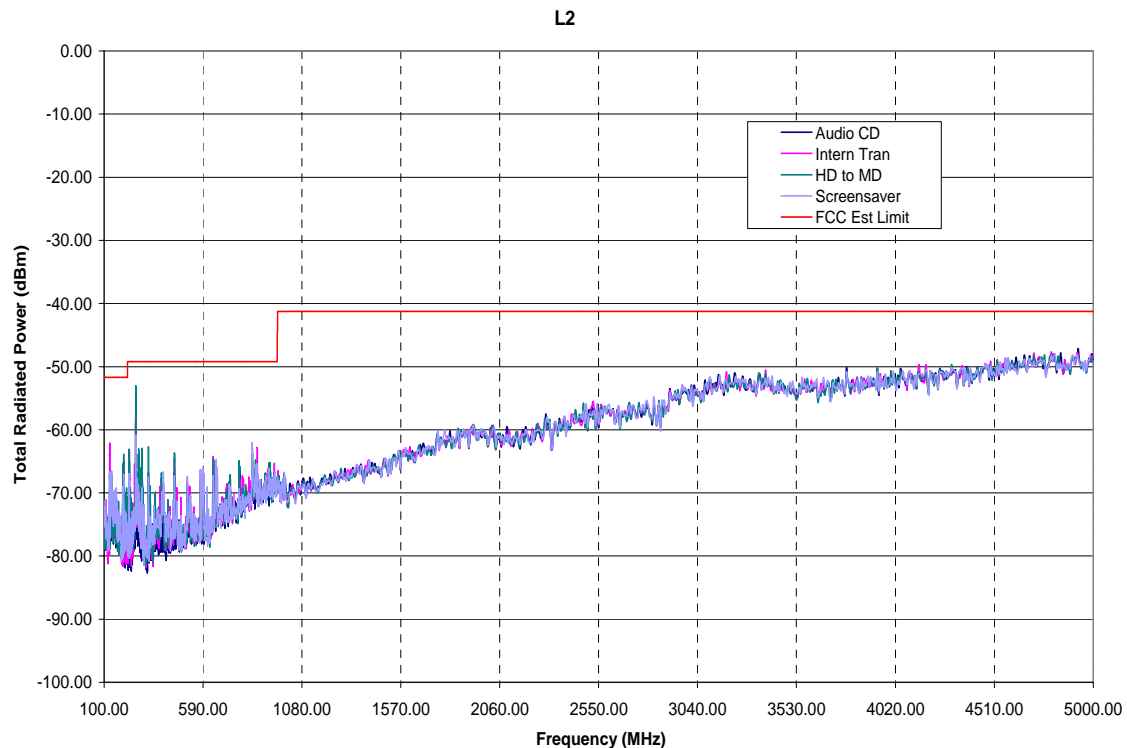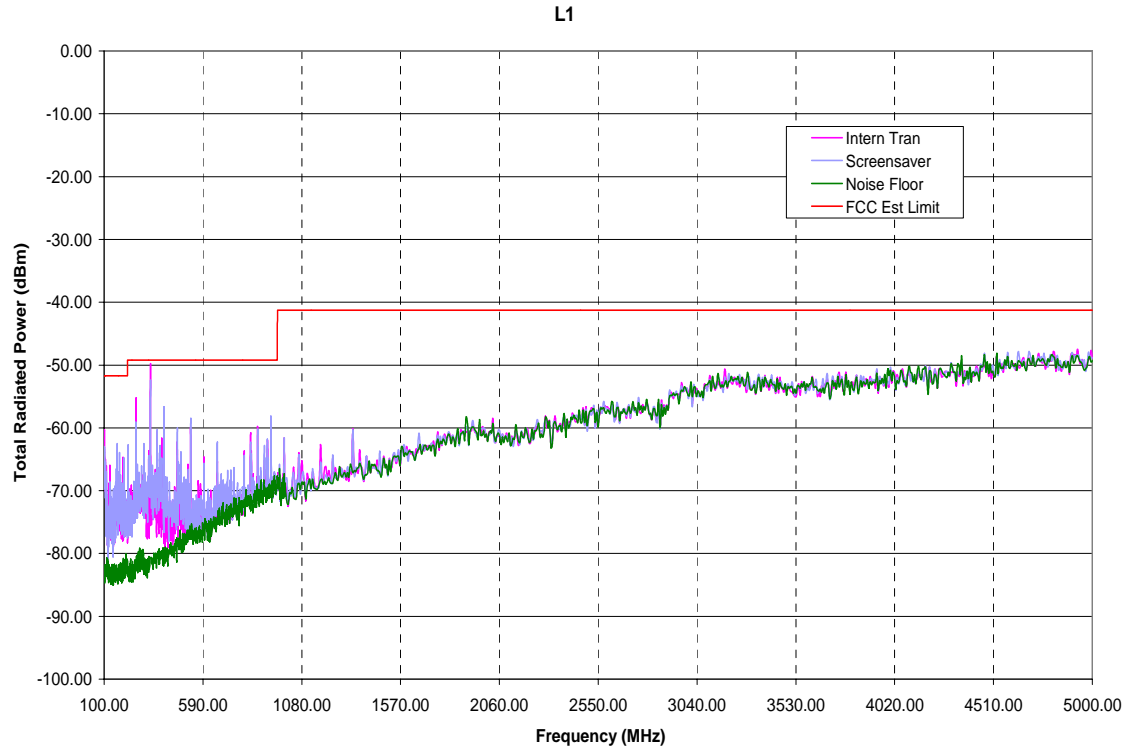
Further study with laptop computers and wireless networks will be necessary in order to determine if the spurious emissions will indeed affect radio navigation equipment on a commercial airplane. The tests will focus on the narrow frequency bands specific to VOR, Glideslope, TCAS, GPS, etc. Further tests of 802.11b and Bluetooth enabled devices in radio navigation bands will include: several 802.11b units or Bluetooth units linked in communication; simultaneous operation of both wireless technologies in the chamber; changing modulation techniques, power setting, and channels as they apply to the appropriate wireless network. The final goal is to formulate a well-devised test plan, which will rigorously test WLANs and laptops being considered for aircraft use by passengers.
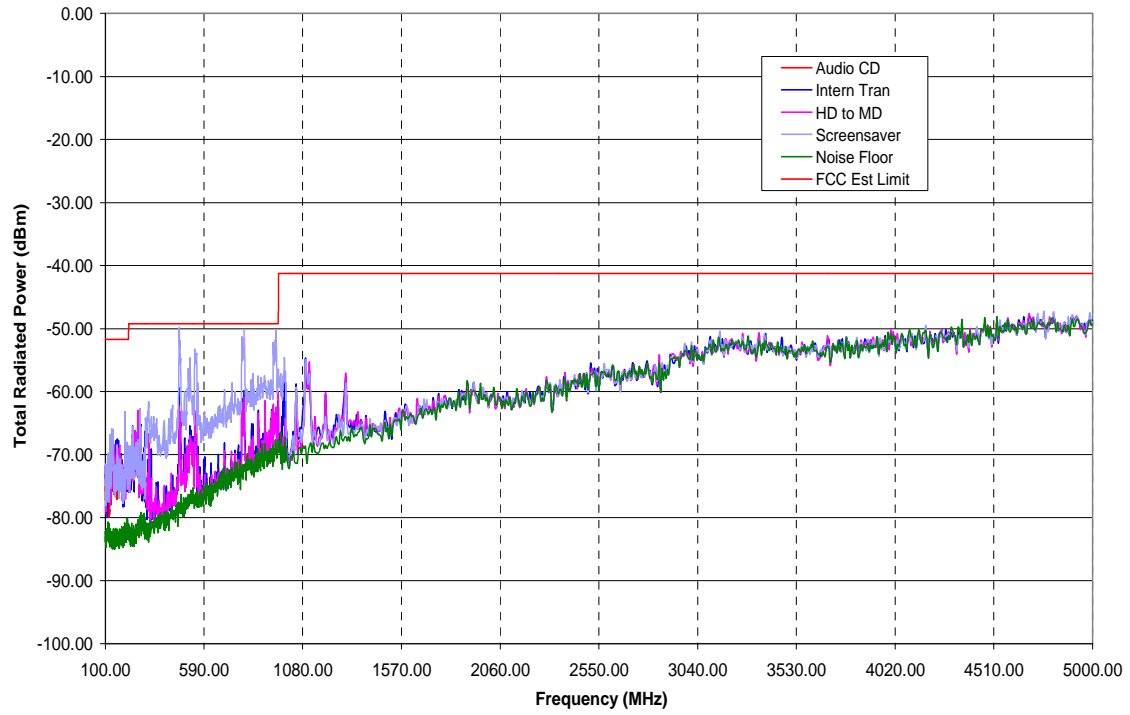
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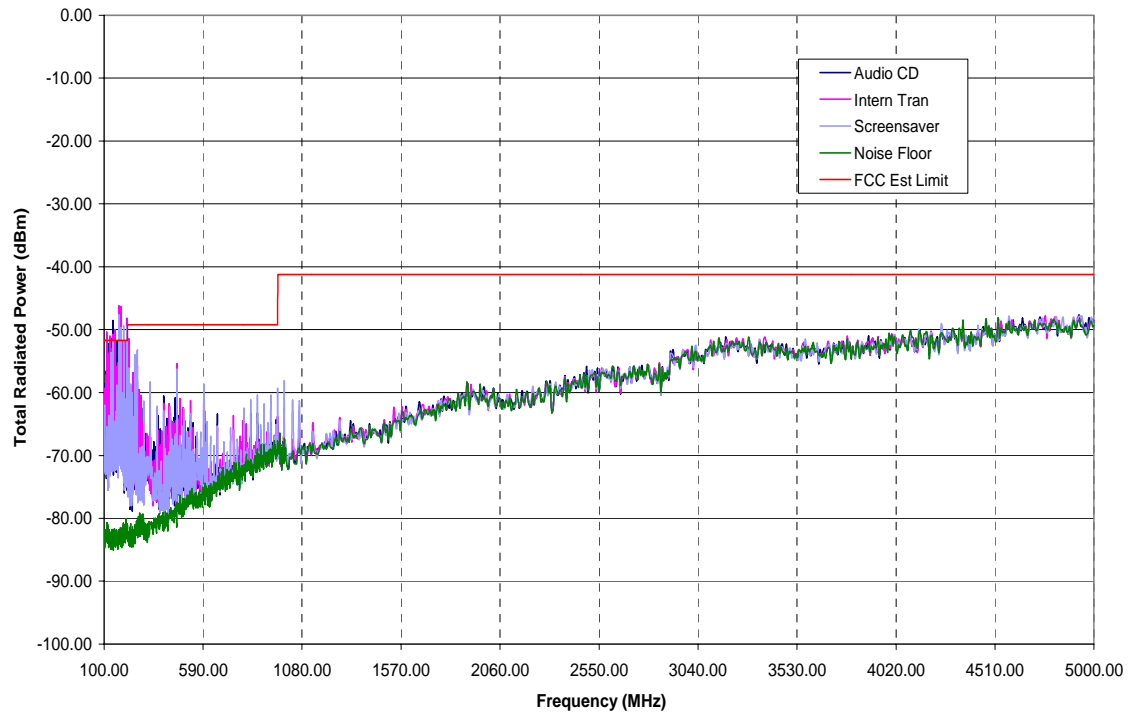# Appendix A: Baseline Test Results from the Laptops

Graphs depicted in this section provide each brand of laptops' envelope of emitted maximum radiated peaks. Furthermore, wireless data can be superimposed on these graphs to deduce the amount of emissions added to the laptop levels.

L1

L2

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L3

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REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE October 2002	3. REPORT TYPE AND DATES COVERED Contractor Report

4. TITLE AND SUBTITLE
Investigation of RF Emissions From Wireless Networks as a Threat to Avionic Systems

5. FUNDING NUMBERS
NAS1-00135
722-64-10-53

6. AUTHOR(S)
Maria Theresa P. Salud

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lockheed Martin Corporation Langley Program Office
Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-2199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/CR-2002-211941

11. SUPPLEMENTARY NOTES
Langley Technical Monitor: Reuben A. Williams

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 32   Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The paper focuses on understanding and obtaining preliminary measurements of radiated field (RF) emissions of laptop/wireless local area network (WLAN) systems. This work is part of a larger research project to measure radiated emissions of wireless devices to provide a better understanding for potential interference with crucial aircraft avionics systems. A reverberation chamber data collection process is included, as well as recommendations for additional tests. Analysis of measurements from devices under test (DUTs) proved inconclusive for addressing potential interference issues. Continued effort is expected to result in a complete easily reproducible test protocol. The data and protocol presented here are considered preliminary.

14. SUBJECT TERMS
Wireless Local Area Network, Emissions, EMI, Aircraft Avionics

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL